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# S1040 in M67: A Post-Mass-Transfer Binary with a Helium-Core White Dwarf

W. Landsman[1], J. Aparicio[2], P. Bergeron[3], R. Di Stefano[4], T. P. Stecher[5]

## ABSTRACT

We have obtained spectra of the yellow giant S1040 in the open cluster M67 using the Goddard High-Resolution Spectrograph (GHRS) and the Faint Object Spectrograph on the *Hubble Space Telescope*. S1040 is a single-lined spectroscopic binary with a 42.8d period that occupies a "red straggler" position in the M67 color-magnitude diagram (CMD), 0.2 mag blueward of the giant branch. A detection of S1040 at 1620 Å with the *Ultraviolet Imaging Telescope* provided evidence that the secondary is a hot white dwarf, and thus that the anomalous location of S1040 in the CMD is likely due to a prior episode of mass-transfer. Our GHRS spectrum shows a broad Ly$\alpha$ absorption profile that confirms the white dwarf identification of the S1040 secondary. A model atmosphere fit to the GHRS spectrum yields $T_{\rm eff}$ = 16,160 K, $\log g$ = 6.7, and a mass of $\sim$ 0.22 $M_\odot$, for an assumed cluster distance of 820 pc and reddening of E(B–V) = 0.02. The unusually low mass derived for the white dwarf implies that it must have a helium core, and that a mass-transfer episode must have begun while the progenitor was on the lower giant branch. We construct a plausible mass-transfer history for S1040 in which it originated as a short ($\sim$ 2d) period binary, and evolved through a blue straggler phase to reach its current state.

[1]Hughes STX Corporation, NASA Goddard Space Flight Center, Laboratory for Astronomy and Solar Physics, Code 681, Greenbelt, MD 20771

[2]Département de Physique, Université de Montréal, Succ. Centre-Ville, C.P. 6128, Montréal, Québec, Canada, H3C 3J7

[3]Lockheed Martin Canada, 6111 av. Royalmount, Montréal, Québec, Canada, H4P 1K6

[4]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

[5]NASA Goddard Space Flight Center, Laboratory for Astronomy and Solar Physics, Code 681, Greenbelt, MD 20771

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## 1. Introduction

S1040 (catalogued by Sanders 1977; =Fagerholm 143) is a yellow giant with $B-V=$ 0.86, and an astrometric and radial velocity member of the open cluster M67 (Girard et al. 1989; Mathieu, Latham, & Griffin 1990). In their radial velocity study of M67, Mathieu et al. discovered that S1040 was a single-lined spectroscopic binary with a circular orbit and a period of 42.8 days. In the M67 color-magnitude diagram (CMD), S1040 occupies a "red straggler" position, 0.2 mag blueward of the giant branch. Janes and Smith (1984) suggested that this anomalous location of S1040 in the CMD could be explained if S1040 were a photometric binary consisting of a star on the lower giant branch and a star near the main-sequence turnoff. However, Mathieu et al. (1990) found no evidence of a secondary correlation peak in their high signal-to-noise spectra of S1040, indicating that the secondary must be considerably fainter than the primary. They also pointed out that the mass function was consistent with a secondary mass as low as 0.18 $M_{\odot}$. To explain the circularization of the orbit, Verbunt and Phinney (1995) suggested that the secondary of S1040 was a white dwarf, and that the white dwarf progenitor must have filled its Roche lobe.

An important clue to the nature of the S1040 secondary was provided by a 1620 Å image of M67 obtained in 1995 March with the *Ultraviolet Imaging Telescope* (Stecher et al. 1997). A total of 16 stars in M67 were detected at 1620 Å, including the 11 hottest blue stragglers, four white dwarf candidates, and S1040 (Landsman et al. 1997). The detection of S1040 at 1620 Å almost certainly implies that the secondary is a hot white dwarf, since a more luminous type of ultraviolet source would be inconsistent with the composite red B–V color. Since a white dwarf secondary makes a negligible contribution to the integrated V magnitude, the peculiar location of S1040 in the M67 CMD is likely the result of an earlier mass-transfer episode. To further elucidate the nature of S1040, we have now obtained observations of S1040 with the Goddard High-Resolution Spectrograph (GHRS) and the Faint Object Spectrograph (FOS) aboard the *Hubble Space Telescope*.

The spectroscopic determination of the fundamental parameters of a post-mass-transfer binary is often problematic, because both components have deviated from single star evolution. Thus the membership of S1040 in the well-studied solar-metallicity open cluster

M67 is particularly fortunate, and we adopt in this *Letter* the cluster distance (820 pc), age (4 Gyr), and reddening (E(B–V) = 0.025) given by Carraro et al. (1996).

## 2. Observations

S1040 was observed on 18 May 1996 with the G140L mode of the GHRS, covering the wavelength region from 1175 Å to 1450 Å, and with the G270H mode of the FOS, covering the region from 2220 Å to 3300 Å. The observation date corresponds to phase 0.54 in the Mathieu et al. (1990) orbit. The exposure time of the GHRS observation was 6582s, and the use of the large ($1.74'' \times 1.74''$) aperture gave a spectral resolution of about 0.8 Å. The exposure time of the FOS observation was 300s, and the use of the large ($3.7'' \times 1.3''$) aperture gave a spectral resolution of about 2.0 Å. Spectra from both instruments were reduced using the software prepared by the GHRS instrument team (Robinson et al. 1992). The GHRS spectrum was further corrected for a $\sim 5\%$ sensitivity degradation below 1200 Å (Sherbert 1996).

## 3. Analysis

The GHRS spectrum of S1040 (Figure 1) shows a broad Ly$\alpha$ absorption that confirms the identification of the S1040 secondary as a hot white dwarf. S1040 is among the faintest white dwarfs ever observed in the ultraviolet, and so despite the deep GHRS exposure, the S/N per resolution element is only about 18. The strong emission in the core of Ly$\alpha$ is due to the Earth's geocorona, and the strength and spectral profile of the emission feature near 1304 Å is also consistent with being entirely due to diffuse gecoronal O I emission. Interstellar lines of Si II $\lambda$1260, C II $\lambda$1335, O I $\lambda$1302, and Si II $\lambda$1304 are clearly present, while other possible absorption features at $\lambda$1180, $\lambda$1329, and $\lambda$1371 are of uncertain origin. The S/N and spectral resolution of the GHRS spectrum is insufficient to determine whether narrow photospheric lines exist in the white dwarf spectrum, such as would be needed for an eventual determination of a double-lined spectroscopic orbit.

We fit the GHRS spectrum using the pure-hydrogen white dwarf model atmospheres of Bergeron et al. (1995). A low-dispersion ultraviolet spectrum is not sufficient by itself to constrain both $T_{\rm eff}$ and $\log g$ in a hot white dwarf, because a good fit is possible at any value of $\log g$(Landsman, Simon, & Bergeron 1996). However, for an assumed value of $\log g$, the best-fit value of $T_{\rm eff}$ and the angular diameter derived from the flux scaling can be used along with a ($T_{\rm eff}$-dependent) theoretical mass-radius relation to derive the white dwarf

distance. Table 1 shows the computed distances to S1040 for a range of assumed $\log g$ values, using the mass-radius relation of Wood (1995) for carbon white dwarfs with thick hydrogen and helium layers. Even for the lowest mass (0.2 $M_\odot$) carbon model available, the computed distance is less than the cluster distance of 820 pc. Qualitatively, the origin of this low mass determination is that a relatively cool $T_{\rm eff}$ is required to fit the broad Ly$\alpha$ absorption profile, so that a large radius (low mass) is needed to reproduce the absolute ultraviolet flux level.

In fact, the use of a carbon composition to compute a mass-radius relation is not realistic for a such a low-mass white dwarf, because the ignition of helium requires a core mass of at least 0.49 $M_\odot$near the tip of the red giant branch (c.f. Marsh, Dillon, & Duck 1995). At high ($\sim$ 50,000 K) temperatures, a helium white dwarf is known to have a significantly larger radius than a carbon white dwarf of the same mass (Vennes, Fontaine, & Brassard 1995), and some modifications in the mass-radius relation might still be expected at the relevant $T_{\rm eff}$ ($\sim$16,000 K) for S1040. Therefore, we have recomputed the derived distances in Table 1, using new evolutionary calculations of the helium-rich core of a giant star whose envelope has been stripped (see Aparicio & Fontaine 1997 for more details). The M67 distance of 820 pc can then be matched using a model with $T_{\rm eff}$ = 16,160 K, $\log g$ = 6.7, and a mass of $\sim$ 0.224 $M_\odot$. The evolutionary time for the white dwarf to reach this $T_{\rm eff}$ is about 75 Myr after ejection of the envelope on the giant branch. Note that, whereas the evolutionary track of a typical 0.6 $M_\odot$ white dwarf crosses into the hottest ($\sim 10^5$ K) region of the HR diagram, the maximum $T_{\rm eff}$ along the 0.22 $M_\odot$ evolutionary track is only about 17,500 K.

The FOS spectrum of S1040 is shown in Figure 2, along with the model white dwarf spectrum derived from the fit of the GHRS spectrum. The white dwarf still dominates the spectrum at 2200 Å, but provides only about 1% of the total flux at 3300 Å. Also shown in Figure 2 is a best-fit Kurucz (1993) model with [Fe/H] = 0.0, $T_{\rm eff}$ = 5150 K and $\log g$ = 3.5, normalized to the reddening-corrected V magnitude of S1040. The scaling required to fit the Kurucz model yields a radius of the yellow giant of 5.1 $R_\odot$. A radius about five times larger than this value would be needed for S1040 to show an eclipse of the white dwarf, assuming the Mathieu et al. mass function, and masses of 1.5 $M_\odot$ and 0.22 $M_\odot$for the primary and secondary.

Figure 2 also shows that the Mg II $\lambda$2800 doublet is observed in emission, with an reddening-corrected integrated flux of $1.87 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. This corresponds to a surface flux of $9.4 \times 10^5$ erg cm$^{-2}$ s$^{-1}$, using the angular diameter derived above. This Mg II surface flux is an order of magnitude larger than the typical values reported for seven M67 giants by Dupree, Hartman, & Smith (1990), and near the upper envelope of the surface

flux values observed in field G giants. The high chromospheric activity level indicated by this Mg II surface flux value, supports the classification of S1040 as an RS CVn binary, as originally suggested on the basis of its X-ray luminosity by Belloni et al. (1993).

Table 2 summarizes the parameters of S1040, as derived in this work and taken from the literature.

## 4. Discussion

The relatively long orbital period of S1040, and the low mass derived here for the white dwarf secondary, place strong constraints on the possible evolutionary history of S1040. An episode of mass transfer must have occured before the white dwarf progenitor developed a core mass which is larger than the mass of the current white dwarf. But if the mass transfer episode began while the donor still had a radiative envelope, then a common envelope would likely occur, leading to a shrinkage of the orbit, in contradiction to the observed 42.8d period. In fact, population synthesis calculations (Di Stefano 1997) indicate it should not be rare for mass-transfer during the subgiant or lower giant branch of the primary (early Case B evolution) to lead to systems similar to S1040. For such systems, a relation between the final orbital period and the mass of the helium white dwarf can be derived by combining the core mass – radius relation for a red giant with the requirement that the red giant always fill its Roche lobe during the mass-transfer phase (e.g. Rappaport et al. 1995). The Rappaport et al. relation predicts a white dwarf mass of $\sim 0.27$ $M_{\odot}$for the S1040 orbital period, while a similar formula of Eggleton (personal communication) predicts a white dwarf mass of 0.25 $M_{\odot}$. These predicted masses are sufficiently close to the white dwarf mass of 0.224 $M_{\odot}$ derived here, to lend confidence in our ability to outline the evolutionary history of S1040.

The basic scenario is that two stars in a relatively close orbit begin an epoch of mass transfer when the more massive star fills its Roche lobe. If the initial orbital period is on the order of days, the donor star will have a helium core mass near or slightly larger than $0.1M_{\odot}$ when mass transfer begins. Until sometime after the masses equalize, the mass transfer rate will be fairly high, governed by the the donor's attempts to re-establish thermal equilibrium as it expands, while its Roche lobe either shrinks or remains close to a fixed volume. After mass equalization, continued mass transfer tends to expand the Roche lobe, even as the donor itself expands, leading to an epoch of stable mass transfer. The mass transfer rate during this latter epoch is governed by the donor's nuclear evolution time scale, which can be longer than it would have been had the donor mass remained constant. Mass transfer ends when the donor's envelope is depleted, leaving the white dwarf remnant we observe.

For concreteness, we have constructed a binary evolution model which yields a system with the approximate parameters derived here for S1040. The final white dwarf mass (0.25 $M_\odot$) and age (5.0 Gyr) in the model are slightly larger than values reported here for S1040, but probably within the observational errors. The model ingredients are described by Di Stefano & Nelson (1996) and Di Stefano (1997), and we note here only that the mass retention factor, $\beta$, is taken to be proportional to the ratio of the donor's thermal time scale to that of the accretor. The initial model masses are 1.24 and 0.82 $M_\odot$, and the initial orbital period is 1.86d. For such a system, Roche lobe overflow occurs after about 4.1 Gyr, when the more massive star has developed a core mass of 0.159 $M_\odot$. After 95 Myr, the component masses have equalized at about 0.98 $M_\odot$(with about 0.1 $M_\odot$ lost from the system), although the orbital period (1.97d), and the donor core mass (0.163 $M_\odot$), have increased only slightly. Stable mass transfer continues for another 765 Myr until the envelope of the donor is depleted, leaving a system with an orbital period of 42.1 d, consisting of a 0.25 $M_\odot$ helium white dwarf and a 1.48 $M_\odot$ blue straggler. In fact, the star is observed as a blue straggler (i.e. the accretor mass exceeds the cluster turnoff mass) during the final $\sim$ 400 Myr of mass transfer.

As noted earlier, comparison with the 0.22 $M_\odot$ evolutionary track indicates that mass transfer in S1040 ended about 75 Myr ago. Thus, within the past 75 Myr the blue straggler in S1040 must have evolved redward to its current location, 0.2 mag blueward of the giant branch in the M67 CMD. Qualitatively, an evolved blue straggler is expected to lie to the blue of the cluster giant branch, but a more detailed calculation than presented in this *Letter* will be needed to follow the temperature and luminosity evolution of the accretor.

Are there other systems similar to S1040? Case B mass transfer is the most likely explanation for the origin of the current M67 blue straggler F190, which has a 4.2d period, although it may not be possible to explain the other M67 blue stragglers as the end products of mass transfer (Leonard 1996). Among the field stars, many of the parameters of AY Cet (= HR 373, K0 IV + wd, P = 56.8d) are similar to those of S1040, including the mass function and the estimated white dwarf temperature (Simon, Fekel, & Gibson 1985). Simon et al. point out that the white dwarf mass in AY Cet could be as low as 0.25 $M_\odot$, provided that its distance is near the the upper limit of that derived from the (large) uncertainty in its parallax. The hot component in the eclipsing binary HD 185510 (K0 III/IV, P = 20.7d) is known to have a low (0.3 $M_\odot$) mass, but whether its atmospheric parameters are consistent with those of a degenerate helium white dwarf is still uncertain (Jeffery & Simon 1997).

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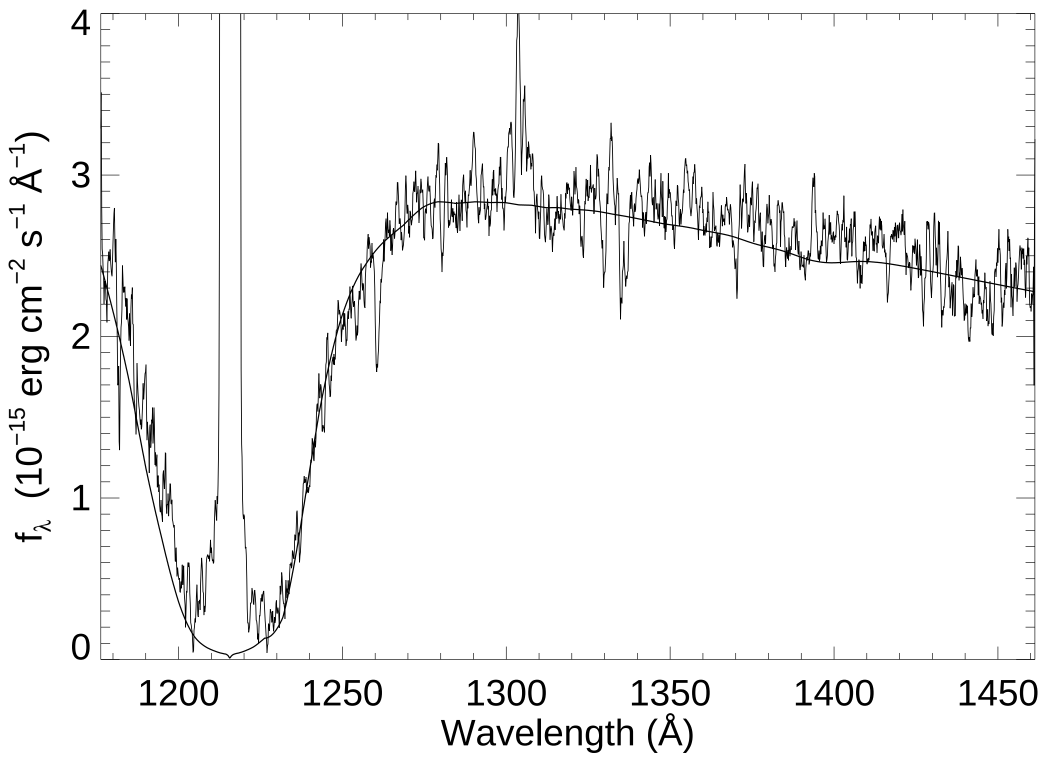


Fig. 1.— GHRS spectrum of S1040. The spectrum has been corrected for a reddening of E(B–V) = 0.02. The thick solid line shows a best-fit white dwarf model with $T_{\rm eff}$ = 16,900 K and log $g$= 7.0.

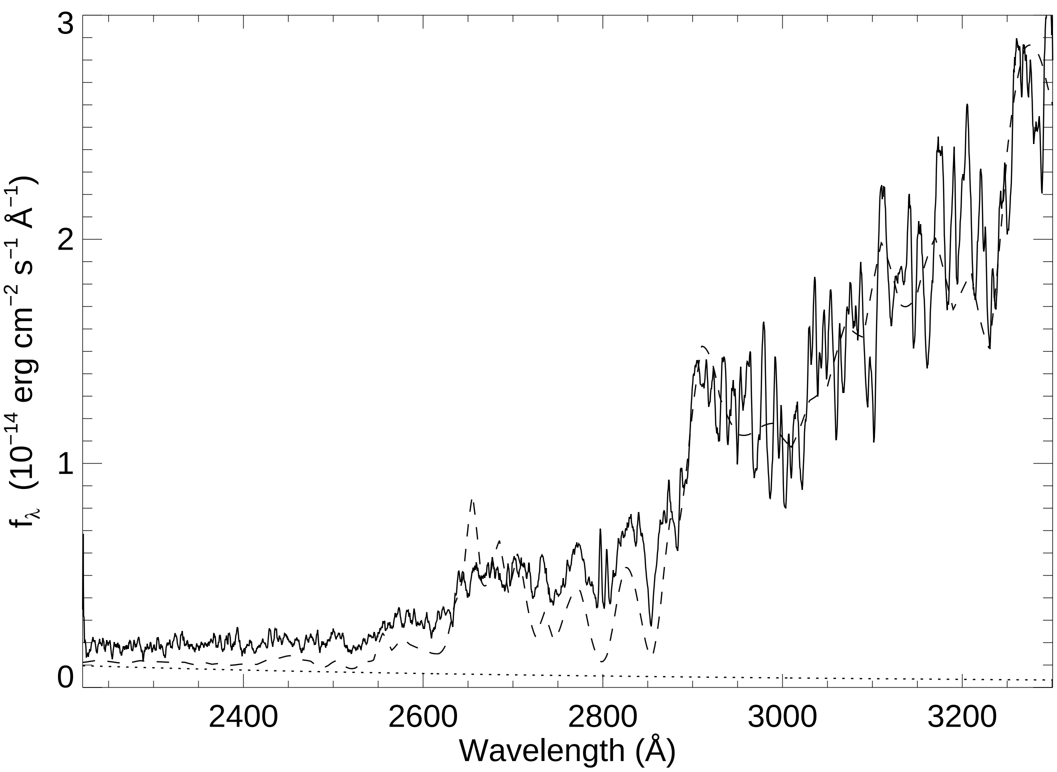


Fig. 2.— FOS spectrum of S1040. The spectrum has been dereddened by E(B–V) = 0.02. The dotted line shows the predicted contribution of the white dwarf, using the parameters derived from the fit of the GHRS spectrum. The dashed line shows the sum of the white dwarf spectrum and a Kurucz model with $T_{\rm eff}$ = 5150 K, $\log g$= 3.5, normalized to the reddening-corrected V magnitude of S1040.

Table 1. White-Dwarf Model Fits

| $\log g$ | $T_{\rm eff}$ | $R^2/D^2$ | $M/M_\odot$ | $d$ (pc) | Compos |
|---|---|---|---|---|---|
| 6.7 | 16,135 | $9.06 \times 10^{-25}$ | 0.223 | 825 | He |
| | | | 0.200 | 791 | C |
| 7.0 | 16,890 | $7.19 \times 10^{-25}$ | 0.262 | 718 | He |
| | | | 0.254 | 714 | C |
| 7.5 | 18,740 | $4.35 \times 10^{-25}$ | 0.39 | 645 | C |
| 8.0 | 20,660 | $2.75 \times 10^{-25}$ | 0.62 | 567 | C |

Table 2. Parameters of S1040

| Parameter | Value | Ref[a] |
|---|---|---|
| V | 11.51 | 1 |
| B–V | 0.86 | 1 |
| Sp.T. | G4 III | 2 |
| Period (d) | 42.8 | 3 |
| K (km $s^{-1}$) | 8.45 | 3 |
| f(m) | 0.00268 | 3 |
| $L_X$ (erg $s^{-1}$) | $3 \times 10^{30}$ | 4 |
| $T_{\rm eff}$(primary) | 5150 K | 5 |
| R (primary) | 5.1 $R_\odot$ | 5 |
| M (WD) | 0.22 $M_\odot$ | 5 |
| $T_{\rm eff}$(WD) | 16,160 K | 5 |

[a]REFERENCES: (1) Janes & Smith 1984, (2) Allen & Strom 1995, (3) Mathieu et al. 1990, (4) Belloni et al. 1993, (5) this work